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LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Preliminary assessment for global warming potential of leading contributory gases from a 40-in. LCD flat-screen television

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Abstract
Purpose As liquid crystal display (LCD) flat-screen televisions increase in popularity, their potential contribution to global warming has received wide attention. This study presents global warming impacts resulting from the life cycle assessment (LCA) of LCD flat-screen televisions for key global warming contributors from the "cradle-to-gate" and use stages of the product's life cycle. The emissions from nitrogen trifluoride (NF_3), a greenhouse gas with a global warming potential (GWP) 17,000 times more potent than carbon dioxide (CO_2), are not monitored in the Kyoto Protocol. Emissions in the cradle-to-gate and use stages were modeled in this study according to their GWP (kg CO_2 equivalent), focusing and analyzing the most significant source of NF_3 emissions.
Materials and methods NF_3 is used during the manufacturing process of LCDs to clean the vacuum chambers. In this study, a system diagram of the cradle-to-gate stage and use stage of a 40-in. LCD television was proposed using the software package Gabi®, particularly investigating NF_3 to determine its possible effects on global warming based on a typical LCA.
Results and discussion The energy inputs in the use stage of the LCD flat-screen television resulted in major global warming impacts, while the contribution of GWP resulting from NF_3 was trivial. However, as energy efficiency continuously improves over time, the GWP resulting from NF_3 may become significant. Findings in this study allow industry to focus on those critical stages of the production life cycle that most directly affect global warming while permitting government agencies to enact proper regulations to help decrease CO_2 equivalent emissions.
Conclusions The preliminary assessment of our LCA also offers manufacturers the ability to determine the largest sources of greenhouse gases and their connection in the life cycle analysis of a product. This extension may help guide legislation and industrial management in the future. For further decision making, an in-depth sensitivity analysis may be needed to strengthen the results.

Keywords Cradle-to-gate · Global warming potential (GWP) · Impact assessment · Life cycle assessment · Life cycle inventory · Liquid crystal display (LCD) · Nitrogen trifluoride (NF_3) · Product life cycle · Use stage

1 Introduction

In the past few years, a new global trend has emerged in many industrialized countries that is only recently beginning to show its potential to directly affect global warming. As a result of this awareness, industrial manufacturing processes have been continuously updating models for the flat-screen television, with the most common type being the liquid crystal display (LCD). In 2008 alone, nearly 100 million LCD televisions were purchased, and this number is expected to rise to almost 194 million units in 2012 (Udell 2008). The average cost of a 32-in. LCD television decrease 50% from 2006, and as prices continue to decline, many consumers are purchasing flat-screen televisions for purely aesthetic reasons (Taub 2009). LCD technology is generally believed to be more environmentally friendly because it consumes less power during the operation phase than other types of televisions (e.g., plasma display panel and cathode ray tube). However, a study (Aoe et al. 2003)

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showed that this common perception is not necessary true if the entire product life cycle is taken into account.

Recent studies have determined that the amounts of nitrogen trifluoride (NF_3), a greenhouse gas with a global warming potential 17,000 times more potent than carbon dioxide (CO_2), are entering the atmosphere at four times the rate than previously expected (Conniff 2008). Hischier and Baudin (2010) first discussed the impact as the flat screen technologies gained increasing market share, and a life cycle assessment (LCA) was conducted for a plasma television device; however, the impacts of NF_3 were not assessed in that study. NF_3 is used in the production of semiconductors, thin film solar cells, and flat-panel displays to clean the process chambers and help remove the residue left behind to enable efficient and correct operation (Air 2009). Prior to the mid-1990s, perfluorocompounds such as tetrafluoromethane (CF_4), hexafluoroethane (C_2F_6), and sulfur hexafluoride (SF_6) were used in these process chambers; however, with the signing of the Kyoto protocol in 1997 these gases became regulated. As a result, several specialty gases were used as replacements to the perfluorocompounds (Tsai 2007). NF_3 gained popularity as a gas that was meant to reduce global warming. The United States Environmental Protection Agency (EPA) began to promote the use of NF_3 as the "best solution" to the problem of cleaning process chambers (Conniff 2008). This process substitution from C_2F_6 and SF_6 to NF_3 was the foundation of the voluntary partnership between the semiconductor industry and the EPA to reduce greenhouse gas emissions by 10% from 1995 levels by 2010. LCD flat screen manufacturers quickly followed, and AIR Products, the largest producer of NF_3, was awarded the EPA's Climate Protection Award (Conniff 2008).

It was not until NF_3 was further studied that its ultimate global warming potential was realized. The gas is 17,000 times more effective at trapping heat than CO_2 and is estimated to persist in the environment for up to 550 years (Conniff 2008). After the study, it was still not considered a global warming concern because only about 2% of the gas was assumed to escape into the air (Patel-Predd 2008). However, in 2008 a new study was published by the Scripps Institution of Oceanography that determined a current NF_3 concentration of 0.454 parts per trillion (ppt) in the atmosphere (Cole 2008) compared to an average concentration of 0.02 ppt in 1978, an astonishing increase of more than 2,000%, or 11% annually. Post study, experts now believe the overall emissions rate is closer to 8% (Conniff 2008). Moreover, NF_3 does not have a known recycling process, such as the carbon cycle for CO_2, which leads to an ever-increasing amount of NF_3 in the atmosphere, especially if the production increases over the next hundreds of years. Additionally, this gas is currently not covered by the Kyoto Protocol, which limits and monitors the production of greenhouse gases (Conniff 2008).

Another concern related to the LCD flat screen's popularity is the ever increasing size of the display, coupled with the fact that Americans are watching more television than in the past (State of California 2009). As technology advances and flat screen prices continue to fall, the average consumer is now able to purchase LCD flat-screen television sizes much larger than any traditional cathode ray tube (CRT) television. For example, the average CRT television size purchased by consumers is 30 in. compared to the average 36 in. LCD. The difference in energy demands between the two technologies is also notable; a traditional 30-in. CRT television uses 101 W of power, while the 36-in. LCD television uses 144 W. When incorporating a popular 40-in. LCD model and its associated 180 W of power, the growing concern over energy demands of the newer and larger LCD televisions is evident.

The hypothesis of this study was that NF_3 resulting from the use of 40-in. LCD televisions is one the leading greenhouse gases (GHGs) that could significantly contribute to global warming potential (GWP). A preliminary GWP assessment was conducted in this study to test the hypothesis using the LCA technique. Possible manufacturing measures and regulatory efforts are discussed that may help identify the most significant NF_3 emission stage from the production, use, and end-of-life phases of a 40-in. LCD flat-screen television.

2 Materials and methods

In 2005, an LCA of the traditional CRT and the LCD desktop computer displays was conducted through the EPA's Design of the Environment Program (Socolof et al. 2005) to establish a scientific baseline for the life cycle environmental impacts of CRTs and LCDs. Although LCA focused on the LCD desktop computer display, the technology and manufacturing processes are very similar to those of the LCD television. That study included the extraction and processing of materials, product manufacturing, product use, and end-of-life disposal (Socolof et al. 2005). Data were gathered from 25 companies representing 14 processes and more than 800 inventory items, including primary and secondary material inputs, utility inputs, air emissions, water effluents, hazardous waste, solid waste, radioactive waste, and radioactivity. The study determined that the single largest consumer of energy in the manufacturing stage was the LCD glass manufacturing (Socolof et al. 2005). Due to proprietary and trade secrets, the availability of information from the LCD manufacturing process and the vast number of inventory items associated with a typical LCD television is limited; therefore, this study focused on those LCD manufacturing processes that

have proven to have the most direct and substantial adverse affects in terms of global warming. We used the Gabi® Educational Version Life Cycle modeling software to analyze, from a life cycle perspective, the effect on global warming, assessing NF_3 (SF_6 replacement in the manufacturing process), electricity consumed in the use stage, and emissions from key stages in the manufacturing process with respect to GWP.

All data used during the LCA were scaled to a functional unit of one 40-in. LCD flat-screen television weighing 12 kg (Jeong and Lee 2009). Each inventory item used was deemed a significant agent of global warming based on prior studies. In the preliminary GWP analysis, the system diagram of the cradle-to-gate stage and use stage of a 40-in. LCD television in its life cycle (Fig. 1) included only processes and associated upstream processes within the system boundary.

2.1 Cradle-to-gate stage (upstream processes)

To determine the amount of NF_3 released from the manufacture of one 40-in. LCD flat screen, several key sources of data must be determined in advance. Of principal importance is the amount of NF_3 produced worldwide. In 2008, the value was estimated somewhere between 4,000 and 7,300 metric tons (Conniff 2008). In that same year, an estimated 100 million LCD flat-screen televisions were produced and shipped globally (Udell 2008). To achieve the LCA, a key assumption must be made to determine how much of the 7,300 metric tons of NF_3 are used to manufacture the 100 million LCD flat screens. While an exact percentage is difficult to determine due to proprietary secrets and the lack of regulatory measures on the gas, an assumption that 35% of NF_3 gas produced was used for LCD manufacturing was employed. This assumption was based on multiple factors, including the predominant use of NF_3 for computer chip making, the much larger size of the LCD panel chambers, and the amount of gas used for the production of solar cells. This amounts to 2,560 metric tons of NF_3 produced in 2008 for LCD manufacturing.

The amount of NF_3 produced per LCD manufactured was determined by using the Tier 2a method from the Intergovernmental Panel on Climate Change methodologies. This method calculates the emissions based on "industry-wide default values for the fraction of the purchased gas remaining in the shipping container after use" (Tsai 2007) and additional factors. The Tier 2a method was used because the default values were estimated based on previous studies, providing a quantitative basis for determining the amount of NF_3 released to the atmosphere. The emissions of NF_3 were estimated based on the following equation:

$$E = (1 - h) \times FC \times (1 - U) \times (1 - a \times d), \qquad (1)$$

where E=NF_3 emissions (metric tons), FC=NF_3 consumption in LCD manufacturing (metric tons), h=fraction of NF_3 remaining in shipping containers after use (dimensionless), U=fraction of NF_3 destroyed in the process, a= fraction of NF_3 used in processes with emission control technologies, and d=fraction of NF_3 destroyed in emission control technologies (Tsai 2007). The amount of NF_3 produced and consumed in the LCD manufacturing business was calculated to be 2,560 metric tons. The industry average of 10% of NF_3 left in shipping containers after use was adopted (Tsai 2007). The fraction of NF_3 destroyed or transformed in the chamber cleaning process typically varies from 0.70 to 0.98; 0.70 was chosen to ensure full accountability of the gas. While not entirely known, the value of 1 was adopted as the fraction of NF_3 used in processes with emission control technologies. The fraction of NF_3 destroyed by emission control technologies varies greatly depending on the type of process used and system efficiency; to serve as an industry average, this paper chose 0.80 as the percent destroyed. When all values are substituted into the above equation, 138 metric tons of NF_3 may escape into the atmosphere as a result of LCD television manufacturing. This is up to 5.4% of the total amount of NF_3 produced for LCD manufacturing and is within the industrial estimate of 2–20% of the gas believed

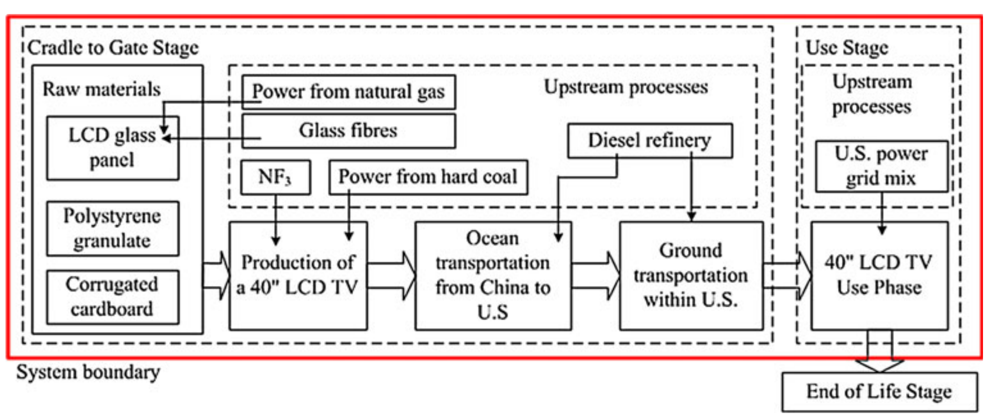


Fig. 1 System diagram of the focused stages in the life cycle

to be released into the atmosphere (Conniff 2008). When scaled to 1 LCD, and based on 100 million LCD televisions manufactured in 2008, 0.0014 kg of NF_3 is released into the atmosphere per LCD television manufactured. From this information we were able to summarize the inventory data for the upstream processes in the cradle-to-gate stage for our preliminary assessment (Table 1).

2.2 Cradle-to-gate stage (manufacturing, packing, and transportation)

One of the most challenging life cycle inventory quantities was the amount of energy needed to manufacture the LCD glass panel. According to the primary data collection phase of the study (Socolof et al. 2005), estimates of total energy consumed during the glass manufacturing energy varied substantially from 4 to 433 kWh/kg, despite extensive attempts to clarify and refine the primary data (Socolof et al. 2005). This study adopted the 4 kWh/kg value based on the European Commission's acceptance of the value for specialty glass manufacturing. A standard 40-in. LCD flat screen's glass panel is 1.758 kg (Jeong and Lee 2009), which amounts to an energy demand of 7.03 kWh.

A significant amount of energy is also invested in the production of 1 LCD television. Energy consumption information specific to a 40-in. LCD flat screen was not immediately available during the research portion of the study. As a result, this study extrapolated the estimated value of energy consumed in the manufacturing stage of a 40-in. LCD flat screen based on earlier studies (Socolof et al. 2005). Socolof et al. (2005) collected primary data from 25 companies between 1997 and 2000 through questionnaires sent to product and component manufacturers in the USA, Korea, and Japan, and determined that approximately 400 kWh of energy is consumed per functional unit of one 15-in. LCD monitor. Most of the datasets for the LCD television were gathered in 1998–1999, so the energy-related data are more than 10 years old. Due to technological advancement and energy saving initiatives assumed to drive manufacturers, the energy required to produce an equivalent 15-in. LCD monitor in today's manufacturing process would be substantially less. However, more energy is required for manufacturing a bigger size LCD monitor. Consequently, this study adopted the value of energy consumption of 490 kWh per 40-in. LCD television manufactured. This amount is consumed in addition to the 7.3 kWh during the glass manufacture and is inclusive of all the upstream energy demand of the LCD manufacturing components.

The last step of the manufacturing process entails the packaging of the item. Typically, the LCD television is packaged with a combination of corrugated cardboard and polystyrene (i.e., typically referred to as styrofoam). The standard weight of packaging material for a 40-in. LCD flat screen was determined to be 1.37 kg (Jeong and Lee 2009). This study used a total packaging product weight of 1.4 kg, with 0.8 kg of corrugated cardboard and 0.6 kg of inside polystyrene packaging material.

The transportation stage is also included in the cradle-to-gate process because it has the potential to add additional amounts of CO_2 to the atmosphere that can accurately be tracked. This study determined that a majority of the LCD flat screens are made somewhere in Asia, typically China. To transport the LCDs to the USA, they must travel roughly 9,600 km via a tanker with an average payload of 105,000 metric tons across the Pacific Ocean to the west coast and from there supplied to different areas in the USA. This study chose Chicago, Illinois, as the final shipping location to represent an average total distance between the east and west coasts. We assumed that a tractor trailer truck with a 3.3-t cargo payload was used to transport the LCD flat screen to its final destination, calculated to be 3,200 km. Based on this information, the inventory data for manufacturing, packing, and transportation processes in the cradle-to-gate stage for our preliminary assessment were summarized (Table 2).

Table 1 Inventory data for upstream processes in the cradle to gate stage

Characteristic	Unit	Value adopted in this study
Total NF_3 produced in 2008	Metric tons	7,300
% of NF_3 for LCD manufacturing	%	35
Units of LCD produced in 2008	Million	100
h	%	10
U	%	70
a	%	100
d	%	80

2.3 Use stage

The second greatest contributor of global warming impacts study was found to be the generation of electricity during the use stage (Socolof et al. 2005). A previous study determined that 28% of the global warming impacts of CO_2 were produced during this stage, set at 4 years (Socolof et al. 2005). To determine the amount of CO_2 produced in the use stage as a result of the LCD consumption, several important factors must be quantified. An average 40-in. LCD television consumes 180 W of power during its use stage. When the television is powered down to the standby stage, it typically consumes about

Table 2 Inventory data for processes in the cradle to gate stage

Characteristic	Unit	Value adopted in this study
Energy consumption (glass manufacturing)	kWh/kg	4
Weight of 40-in. LCD glass panel	kg	1.758
Energy consumption (40-in. LCD TV)	kWh/kg	490
Weight of corrugated cardboard	kg	0.8
Weight of polystyrene	kg	0.6
Ocean transportation distance	km	9,600
Ocean transportation payload	Metric ton	105,000
Ground transportation distance	km	3,200
Ground transportation payload	Metric ton	3.3

5 W of power (Jeong and Lee 2009). To determine the amount of electricity consumed and resulting CO_2 produced, the time that the television is in use must be set. This study chose an operation time of 4.9 h/day, a standby time of 16.9 h/day, and a disconnected time of 2.2 h/day, as suggested by Jeong and Lee (2009). The useful life of an LCD television is determined by several variables and can change depending on the system, the environment, and the quality of manufacturing. Thus, the useful lifetime of a LCD was chosen to be 7 years based on the data from Jeong and Lee (2009). The annual electricity consumption during the use stage can then be determined using the following equation:

$$\begin{aligned} &\text{Annual electricity consumption(kWh/year)} \\ &\quad = (\text{operation time} \times \text{energy consumption in operation}) \\ &\qquad + (\text{standby time} \times \text{energy consumption in stand} - \text{by}). \end{aligned} \quad (2)$$

With this equation, the annual electrical consumption is calculated to be 360 kWh. Based on a useful life of 7 years, a LCD television may consume 2,500 kWh of electricity. Using this information, the inventory data for processes in the use stage for our preliminary assessment was summarized (Table 3).

Table 3 Inventory data for processes in the use stage

Characteristics	Unit	Value applied in this study
Power consumption (40-in. LCD operation)	Watt	180
40-in. LCD operation hours per day	Hour/day	4.9
Power consumption (40-in. LCD standby)	Watt	5
40-in. LCD standby hours per day	Hour/day	16.9
Lifetime of a 40-in. LCD TV	Year	7

3 Results and discussion

3.1 Cradle-to-gate—impact assessment

The cradle-to-gate stage of the LCA represents the inventory for producing the valuable product (PE International 2010), which in this case is a 40-in. LCD flat-screen television. A Gabi® model was created in this cradle-to-gate stage of the LCA (Fig. 2) that encompasses the manufacturing and transportation stages of the product's life cycle. A major part of the modeling formulation is the graphical representation of the GWP of different gases (Fig. 3), which clearly indicates that CO_2 is the leading contributor to global warming in the cradle-to-gate stage.

In the production of one 40-in. LCD flat screen, 524 kg of CO_2 is emitted through the different processes, accounting for 86% of the relative contribution to GWP. The second largest contributor is not NF_3, which was expected, but volatile organic compounds (VOCs) to the air. VOCs release 55 kg of CO_2 equivalent, accounting for 9% of the relative contribution to GWP. Gabi® calculated that the 0.0014 kg of NF_3 estimated to escape into the atmosphere was equivalent to producing 24 kg of CO_2, contributing only 4% to GWP in this stage. Nitrous oxide, which was produced largely from the electrical production using coal as a fuel source, generated 4 kg of CO_2 equivalent, accounting for 0.6% of the relative contribution to GWP. Contributions from SF_6 were negligible.

Of the specific processes that emitted the most significant amounts of CO_2 gases (Fig. 4), the largest significant source in the cradle-to-gate stage was the energy needed during the manufacturing process. This energy is required in the assembly of the LCD flat screen and is inclusive of all upstream energy demands with the exception of the LCD glass panel manufacturing (40-in. LCD flat screen process, see Fig. 2). The energy supplied in the manufacturing was assumed to be derived from a coal-powered electric plant. Thus, 502 kg of CO_2 was produced per each LCD flat screen, which signifies the massive amounts of CO_2 release associated with all television components manufactured per each LCD flat screen. This value seems to dwarf the counterparts in other process steps.

The second largest contributor to GWP in the cradle-to-gate stage was the production of the LCD glass panel. The amount of CO_2 emitted during this process is the sum of the CO_2 emitted in the manufacturing of the glass panel, denoted by the flow of the "Power from natural gas," and the emissions from the production of the glass fibers. The total amount of CO_2 emitted from the manufacture of LCD glass was determined to be 15 kg. The amount of CO_2 emissions generated from the transportation of the LCD flat screens was calculated to be 5.5 kg, which is the sum of the CO_2 emissions from the bulk commodity carrier (ship), the solo truck, and the

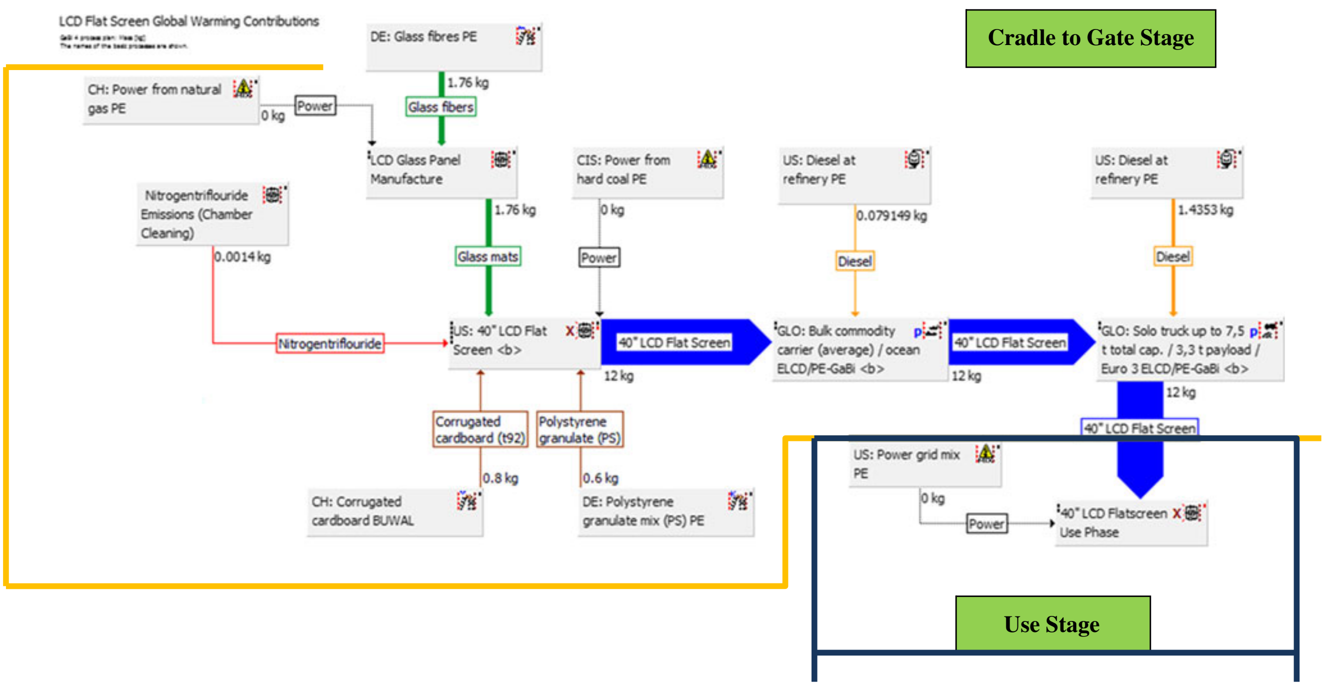


Fig. 2 A 40-in. LCD flat screen life cycle profile

manufacturing of the diesel fuel needed to power these means of transportation. Transportation-related emissions of CO_2 were determined to be minimal when compared to the electrical consumption during the manufacturing process.

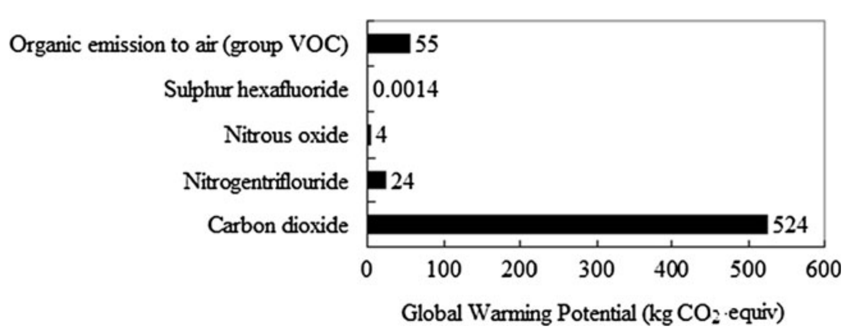
3.2 The use stage–impact assessment

The only input in the use stage is the electricity needed for the operation of the LCD flat screen. The use phase (see Fig. 2, Use Stage) is based on the average of data acquired from the study by Jeong and Lee (2009). The study used the Gabi® 4 flow "US: Power grid mix" as the electrical production source for the 2,500 kWh energy demand to more appropriately model the different types of electrical production found in the USA. From the different GHGs produced as a result of the electrical production (Fig. 5), we calculated that 2,015 kg of CO_2 equivalent were produced from a 40-in. LCD flat screen over a 7-year lifespan: 1,951 kg of CO_2 were released, accounting for 97% of the GWP; 55 kg of CO_2 equivalent was produced from VOCs, accounting for 2.7% of the GWP; 8 kg of CO_2 equivalent was generated from nitrous oxide, accounting for 0.4% of the GWP; and SF_6 emissions were calculated to be negligible.

Findings clearly indicate that the use stage contributes much more than the cradle-to-gate stage to the total GWP in the LCA of a 40-in. LCD television based on the inventory data used in the model (see Tables 2 and 3). However, this value is entirely dependent on the life expectancy of the LCD flat-screen television. The longer the life span, the more emissions summed in an LCA; however, longer life spans decrease the net amount of CO_2 released to the atmosphere because of the energy and resources saved from manufacturing another LCD flat screen to take its place. Although we did not take this substitution effect into account in our study, once the largest contributor is identified, practices to decrease emissions can be determined.

Up to this point, a holistic view of the life cycle profile of a 40-in. LCD flat-screen television (see Fig. 2) encom-

Fig. 3 GWP of five most significant greenhouse gases in cradle-to-gate stage



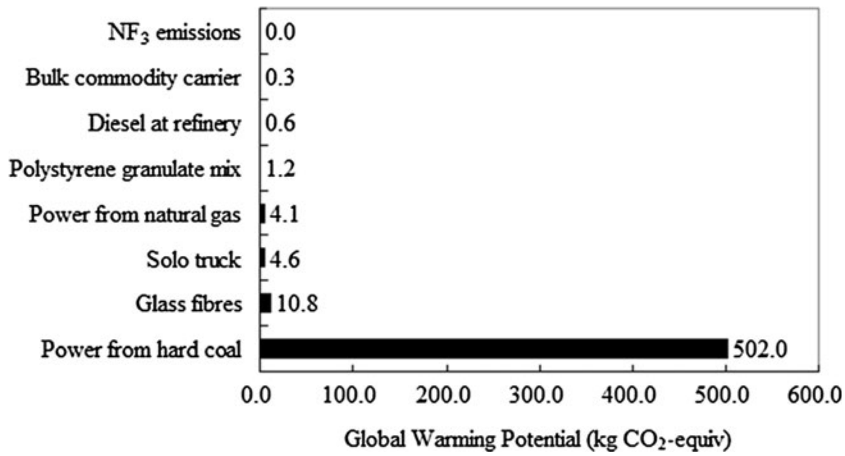


Fig. 4 Carbon dioxide emissions from key manufacturing and transportation stages

passes the processes found in the cradle-to-gate stage, including the transportation and manufacturing stages, and the electrical demand of the use stage. To prioritize the countermeasure against the impact of GWP associated with the manufacturing of LCD flat-screen television, the GWP of the five top GHGs in the life cycle of the LCD flat-screen television can be sorted using the "weak point analysis tool" offered by Gabi® (Fig. 6). The bar graph clearly indicates that CO_2 is the leading GHG in the manufacture and use stages of an LCD flat-screen television. During the manufacture and use stages of an LCD flat-screen television, 2,476 kg of CO_2 can be emitted, accounting for 94% of the relative contributions to GWP. Organic emissions were the second leading contributor to GWP with 110 kg of CO_2 equivalents being emitted, accounting for 4% of the GWP. NF_3 was the third leading global warming contributor with 24 kg of CO_2 equivalent being emitted, accounting for only 1% of the GWP. Nitrous oxide emissions totaled 12 kg of CO_2 equivalent, and contributed 0.5% toward the GHGs emitted. Sulfur hexafluoride emissions were negligible. In particular, these observations produce a clear picture in regard to the relative insignificance of NF_3 to GWP.

Because CO_2 is the largest component contributing to the GWP, the largest sources of this GHG must be analyzed to improve legislation and industrial management (see Fig. 6). The largest CO_2 source in the life cycle of the 40-in. LCD flat screen can be identified as the electrical consumption required in the use stage as indicated by Gabi® (Fig. 7). With the aid of Gabi®, the use stage generated 1,951 kg of CO_2 emissions when using the average electricity from the US electric grid, accounting for 75% of the total CO_2 emissions produced. The second leading contributor of CO_2 emissions was the electrical power consumed in the manufacturing phase of the life cycle, which generated 502 kg of CO_2, accounting for 19% of the CO_2 emissions. The manufacture of the LCD glass panel produced 14.9 kg of CO_2, 0.5% of total CO_2 emissions, and the transportation via truck accounted for 4.6 kg of CO_2, and 0.2% of total CO_2 emissions. Manufacturers could use this information to develop countermeasures to reduce the GHG emission over the entire life cycle with prioritized strategies.

3.3 Sensitivity analysis and discussion

Our preliminary assessment indicates that NF_3 is not a significant (less than 1%) contributor to the total GWP in the LCA of a 40-in. LCD television. This finding was largely based on the assumptions employed during the

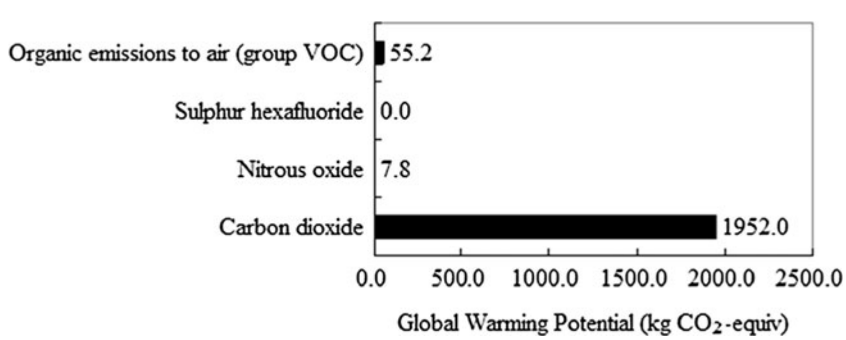


Fig. 5 GWP of four most significant greenhouse gases in use stage

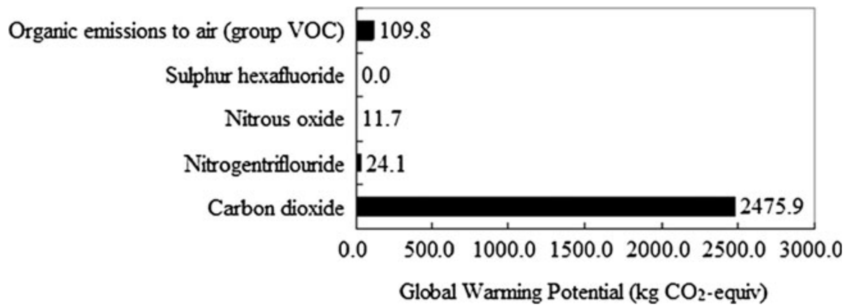


Fig. 6 GWP of five most significant greenhouse gases in 40-in. LCD flat screen life cycle profile

study and the related ambiguity of the true amounts of NF_3 that may possibly be released to the atmosphere as a result of emissions from the vacuum chambers. Much of the ambiguity related to NF_3 is the amount produced annually. This study used an upward estimate of 7,300 metric tons based on estimates by Air Products, the largest manufacturer NF_3 (Conniff 2008). We calculated that 138 metric tons were released to the atmosphere, which is 5.4% of the 2,560 metric tons assumed to be used by the LCD flat-screen television market. Some estimates have ranged as high as a 16% emission rate for the gas, which, in this study, would equate to a CO_2 equivalent of 69 kg emitted to the atmosphere, resulting in 4% of the relative contribution to GWP. This amount is still deemed much smaller than the other contributors considered in the context of this LCA.

This study also made a key assumption that all manufacturers used a control technology to reduce NF_3 emissions, but this may not be true. Some companies may have simply replaced C_2F_6, another gas used in the vacuum chamber cleaning process, with NF_3 while changing nothing in the emission control technology. If so, the manufacturing process could emit 20% of the NF_3 gas used in the manufacturing process directly to the atmosphere (Conniff 2008). Such a change in our calculation basis may lead to a slightly larger GWP due to the use of NF_3, but the level of GWP associated with NF_3 is still deemed trivial relative to other contributors. Although other parameters may vary from case to case, the variance of the sensitivity analysis outputs would not be large enough to alter the current conclusion because CO_2 is dominant relative to all other GHGs involved in this LCA.

4 Conclusions

The LCA conducted in this study for a 40-in. LCD flat-screen television indicated that the largest contributor to GWP was the massive amount of CO_2 emitted to the atmosphere during the use stage. The second largest GHG, or group of gases, that produced the highest GWP was the organic emissions, VOCs. NF_3, which contributed less than 1% to the total GWP, ranked third based on the Gabi® outputs. NF_3 is released from one stage of the product life cycle in which the LCD-producing industry can control 100%, whereas the CO_2 emissions occur largely in secondary and tertiary industry sectors, such as in the transport sector and the energy producing sectors. This implies that improving the energy consumption rate of LCD televisions is the most favorable suggestion for reducing the GWP impacts from the manufacturer perspective. Due to this finding, the hypothesis of this study that predicted NF_3 used for the 40-in. LCD flat-screen television production would significantly contribute to GWP is rejected based on the inventory data we used in this preliminary assessment. However, the GHG emissions from the use stage continue to decrease; therefore, the result should not be interpreted to mean that the impact of NF_3 is negligible for manufacture of LCD televisions because the assessment portfolio is dynamically changing. Specifically, as energy efficiency of the manufacturing process continuously improves over time, the GWP resulting from using NF_3 as a chamber cleaning gas may become significant because of increasing impact of GHG emissions caused by NF_3. Therefore, routine assessments to evaluate the impact of NF_3, a greenhouse gas with a global warming potential 17,000

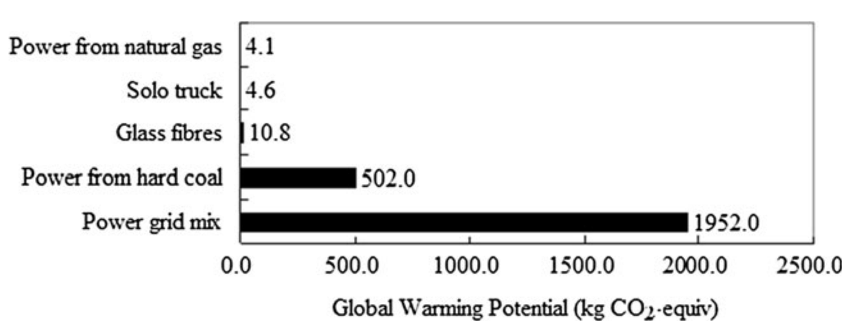


Fig. 7 GWP of five most significant unit processes in 40-in. LCD flat screen life cycle profile

times more potent than CO_2, are valuable. The preliminary assessment of our LCA also offers manufacturers the ability to determine the largest sources of GHGs and their connection in the life cycle analysis of a product. This extension may help guide legislation and industrial management in the future. For further decision making, an in-depth sensitivity analysis may be needed to strengthen the results.

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